Superconductor Technologies Inc. (formerly Conductus)

A Superconducting Hybrid Switch

By the early 1990s, more and more researchers were searching for ways to use a phenomenon that occurs at ultra-low temperatures, known as superconductivity, to address the limitations of conventional integrated circuits (ICs) at normal operating temperatures. The complexity of computation and communications circuits, coupled with the increasing demands on speed, will ultimately exceed the capabilities of semiconductor-based technology. Researchers believe that superconductivity, along with cryogenic operation of semiconductor circuits, could ultimately be used to produce electronic systems with unprecedented performance.

Research in superconductivity, which was a new, challenging, complex, and barely tested technology in electronic applications, was considered extremely risky for commercial applications. As a result, firms who sought to study superconductivity found it difficult to obtain private venture capital. In 1991, a joint venture led by Conductus applied for Advanced Technology Program (ATP) funds to pursue this research, and funding was awarded in 1992. The joint venture, which comprised several private companies and universities, defined the purpose of the project as twofold: 1) to design, build, and test a hybrid-technology switch to demonstrate high-throughput communication switching using components based upon several technologies operating at different temperatures; and 2) to demonstrate the ability to integrate these disparate technologies into a single system. If the project were successful, it would demonstrate that ICs based on superconducting technology could be integrated into a high-speed electronic system, along with other high-performance technologies, to create a viable approach to future communications systems.

Although the joint venture met most of its project goals, their prototype superconducting switch did not demonstrate potential performance sufficiently superior to competing technologies to warrant near-term commercialization. Conductus ceased its efforts in high-speed electronic circuits in 1998 to focus entirely upon microwave communications applications. The company was acquired by its competitor Superconductor Technologies Incorporated in 2002.

COMPOSITE PERFORMANCE SCORE

(based on a four star rating)

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Research and data for Status Report 91-01-0134 were collected during February - May 2004.

Superconductivity: A New Solution for Excess Resistance in Semiconductors?

Superconductivity is a property exhibited by a wide variety of electrical conductors that results in the complete cessation of electrical resistance at extremelylow temperatures, typically not many degrees above absolute zero (0 K on the kelvin scale). Superconductors have been widely used commercially to produce high-powered magnets for magnetic resonance imaging (MRI) medical scanners and to a lesser extent in other applications. Superconducting materials with higher operating temperatures (77 K and above), which are known as “high-temperature superconductors,” were discovered in the 1980s and have enabled additional applications such as the use of superconducting filters for cellular communications.

Since the 1960s, researchers have been developing integrated circuits (ICs) based on superconducting switching devices known as Josephson junctions. These devices have extraordinarily fast switching speeds and use only 1/1000 the electrical power of semiconductor transistors. However, because of limited resources devoted to developing the technology, as well as the intrinsic complexities associated with operating circuits at ultra-low temperatures, superconducting IC technology has never reached a mature enough level of development to successfully compete with conventional approaches. The expectation of the superconducting research community has been that conventional technology would ultimately reach its performance limits and then superconducting technology could take over.

The challenge of increasing speed in electronic circuits is chiefly affected by three limitations:

- The intrinsic speed of the device itself depends on the circuit design, materials, and ultimately the underlying physics by which the device operates.
- The time required for signals to travel through the device circuits drives the increasing miniaturization of the circuits.
- The inability to dissipate the heat generated by the circuits as they become denser causes the highly dense circuits to literally cook themselves to death.

Superconducting circuits can theoretically address these limitations because they are intrinsically faster than semiconductor circuits. They can carry currents in much narrower conductors and can dissipate far less energy than semiconductor circuits. High-speed network switching, a rapidly growing technology requirement in the modern Internet-enabled world, provided the ideal challenge for advanced electronic circuits and appeared to be the area where superconducting circuits could have the greatest impact.

Joint Venture Proposes a Superconducting Prototype Test Switch

In 1991, a joint venture proposed to build and test a multiple-temperature prototype test switch to demonstrate a circuit using high-capacity fiber optic data inputs and superconducting memory and logic circuits. The team consisted of project leader Conductus (now part of Superconductor Technologies), TRW (now Northrop Grumman Space Technology),

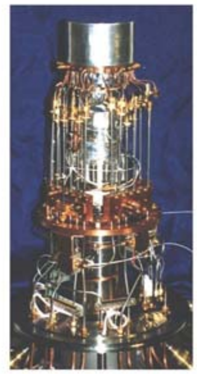

Figure 1. The top cylinder is the shielding can that holds the 4 K circuits (DSP chip). The rigid coaxial cables coming down from the perimeter of the top cylinder are the high-speed fiber optic data lines from the 4 K compartment to the 77 K compartment below. Everything shown in the illustration was then encased in an outer vacuum jacket (not shown). The interior of the vacuum jacket was cooled to maintain the temperatures of the components inside.

Hewlett Packard, the University of California at Berkeley, and Stanford University.

Conductus received Small Business Innovation Research funding, but the monies were only sufficient to support rudimentary research into high-speed circuits. The complex design and testing of a prototype device required additional funding. The joint venture partners were unable to obtain private funding because of the high risk of building a test switch, so they applied to ATP in 1991 and received an award for a five-year project in 1992.

The joint venture partners proposed to design and construct a prototype signal processing system. The goal of the prototype was to demonstrate that a system using standard IC technologies, semiconducting random access memory (RAM), and a digital signal processor (DSP) chip could operate with greater speed and less power loss at three operating temperatures. The prototype's components would operate at the following temperatures: the DSP at 4 K, the memory chips at 77 K, and a supervisory room-temperature workstation at 300 K, or 20°C (these components are shown in Figure 1). The target throughput speed of each port on the DSP was 10 gigabits per second (Gb/s), and the target power loss was 1/1000 that of a conventional semiconductor operating at room temperature. (Power loss is normally caused in room temperature switches by resistance.) More broadly, the switch designers hoped to demonstrate a generic technology that would have a wide range of applications, including memory circuits equivalent to medium-scale integration (MSI, or hundreds of transistors on a chip) and large-scale integration (LSI, or thousands of transistors on a chip).

Difficulties Force the Team to Modify Technical Goals

Over the five-year project, the partners pursued several goals in order to build the prototype system, such as developing the capability to manufacture superconducting large scale integration (LSI) logic circuits and to build a DSP chip based on five generic chip types. However, the team encountered technical difficulties; therefore, starting in late 1992, they began to modify several of their goals. In 1993, after the completion of its first-year activities, Hewlett Packard withdrew from the joint venture. The company had brought computational expertise to the project, so their withdrawal led the venture leader, Conductus, to reevaluate the design and goals of the project. Primarily, Conductus redirected the demonstration focus of the program from computation circuits to communications circuits and, hence, the network switch became the central goal of the program. Subsequently, the team amended the project's goals in minor ways several more times before the project ended.

The hybrid switch designers hoped to demonstrate a generic technology that would have a wide range of applications.

Over the next few years, the partners made steady progress in building the prototype hybrid switch. During this time, Conductus kept current with developments in the field of superconductivity and solicited expertise from the University of California at Santa Barbara and the Lawrence Livermore National Laboratory.

Team Demonstrates Prototype Hybrid Switch

Despite the numerous technical difficulties that the team encountered on this extremely complex project, they demonstrated a prototype hybrid switch in July 1997. Data were transmitted to the four input channels and from the four output channels in the DSP component of the switch via a 10 Gb/s supercooled optical interface for each channel. However, the maximum data rate demonstrated was 8 Gb/s per channel, not the 10 Gb/s intended. According to the lead project engineer, Randy Simon, this lower rate was probably due to the limitations of the so-called driver circuits that amplify the low signal levels of the superconducting circuits to the higher signal levels required by the other components of the switch. The superconducting switch IC itself and these driver circuits operated at 5 K, while the circuits that directly interfaced with the optical components operated at 77 K .The switch system demonstrated that a multiple-temperature design could successfully combine superconducting circuits with cooled semiconductors and room-temperature optical components using a variety of input and processing technologies. Simon noted that falling short of the 10 Gb/s speed goal was not a factor in determining the commercialization prospects of the technology. The partners did not pursue commercialization because of the advancing progress of conventional technology, coupled with the magnitude of resources that would be required to make the superconducting approach viable.

The switch system demonstrated that a multiple-temperature design could successfully combine superconducting circuits with cooled semiconductors and room-temperature optical components.

After the successful switch demonstration, project partners attempted to solicit funding from telecommunications companies, but none were interested in funding additional research efforts. This forestalled the joint commercialization that Conductus had originally planned to pursue with other companies. Conductus, therefore, focused its business on short-term applications of superconducting filter technology, thereby ending all its efforts on high-speed circuit technology. The company was subsequently acquired by its primary competitor, Superconductor Technologies Inc. in 2002. Although no commercialization resulted from this project, Conductus was awarded three patents, one during the project and two after project completion. Moreover, the joint venture members published 17 articles and made one presentation related to the technologies.

One of the project's subcontractors, High Precision Devices, Inc. (HPD) of Boulder, Colorado, has been able to apply knowledge it gained on the ATP-funded project to its work in cryogenic technology for superconducting electronics. The company originally provided the joint venture partners with cryoprobes, multichip modules, chip mounts, and other superconducting hardware. As of 2004, HPD has built cryogenic sample holders, chip mounts, voltage probes, cryostats, and liquefied gas storage containers for government and university research labs, as well as for private companies located in the United States and in many foreign countries. According to company founder and President Bill Hollander, this work is increasingly important to HPD and accounted for about 25 percent of its $1.5 million in sales for 2004. HPD was founded in 1993 with two employees and had sales of $200,000 that year. HPD now employs 15 engineers, instrument makers, and technicians.

Conclusion

A joint venture consisting of Conductus (now part of Superconductor Technologies), TRW (now Northrop Grumman Space Technology), Hewlett Packard, the University of California at Berkeley, and Stanford University successfully built a prototype high-speed network switch that incorporated disparate technologies that were able to operate at several different temperatures. The project team's demonstration of the switch met the original project goals to successfully combine superconducting integrated circuit technology, cryogenically cooled semiconductor circuits, and optical components in an integrated system.

According to Conductus project lead Randy Simon, this diverse joint venture would not have formed without ATP funding. In addition, ATP business and technical contacts at Federal Labs provided oversight to the project that helped Conductus reevaluate its goals after the team experienced major technical failures, such as difficulty in designing and manufacturing the logic switch for the prototype demonstration. Technologies used in the project, such as the ultra-low temperature digital signal processor circuits, have not shown much progress. More research is needed in all aspects of superconductivity. The team shared its project knowledge through three patents, 17 published articles, and one presentation. In addition, the project's requirements assisted High Precision Devices of Boulder, Colorado, in establishing itself as a leading supplier of test devices to the global superconductor industry.

PROJECT HIGHLIGHTS
Superconductor Technologies Inc. (formerly Conductus)

Project Title: A Superconducting Hybrid Switch (Hybrid Superconducting Digital System)

Project: To develop manufacturing, packaging, and multiple temperature environments to combine superconducting logic chips, optical fibers, and room-temperature hardware in a single operating switch system.

Duration: 8/1/1992-7/31/1997 (the project was extended to 5/1998)
ATP Number: 91-01-0134

Funding (in thousands):

ATP Final Cost	$7,391	50%
Participant Final Cost	7,426	50%
Total	$14,817	

Accomplishments: The joint venture team led by Conductus developed and successfully tested the first hybrid technology and temperature test switch at superconducting temperatures.

The project received the following patents for technologies related to the ATP-funded project:

- "Ultrahigh speed laser"
  (No. 5,651,016: filed May 30,1996; granted July 22,1997)
- "Digital optical receiver with instantaneous Josephson clock recovery circuit"
  (No. 5,963,351: filed April 29, 1997; granted October 5, 1999)
- "On-chip long Josephson junction (LJJ) clock technology"
  (No. 6,331,805: filed June 22, 2000; granted December 18, 2001)

Commercialization Status:
Commercialization of the technology developed and tested during this ATP-funded project was not pursued by Superconductor Technologies Inc. (STI), the company that acquired Conductus. According to Randy Simon, formerly of STI, this was probably due to a lack of interest in the technology on the part of the semiconductor and communications industries. However, one the project's subcontractors, High Precision Devices, which manufactured prototype high-temperature superconductivity (HTS) devices, currently earns about $375,000 a year that is attributable to its involvement in the ATP-funded project. The company started in 1993 with 2 employees and now has 15.

Outlook: The outlook for this technology is poor. HTS-integrated circuit research and development remains uncertain due to a lack of funding.

Composite Performance Score: *

Number of Employees: 133 at project start; 275 as of December 2004.

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Publications:

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Presentations:

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